

1 PATENT APPLICATION

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7

8 Title: Spacecraft Off-Gimbal IRU Precision Payload Pointing  
9 and Disturbance Rejection System  
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11 SPECIFICATION

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13 Statement of Government Interest  
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15 The invention was made with Government support under  
16 contract No. F04701-00-C-0009 by the Department of the Air  
17 Force. The Government has certain rights in the invention.  
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19 Field of the Invention  
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21 The invention relates to the field of payload pointing  
22 systems and inertially stabilized spaceborne gimbaled pointing  
23 and tracking systems. More particularly, the present invention  
24 relates to off-gimbal pointing system with base motion  
25 disturbance rejection for precise pointing of a payload  
26 pointing system.  
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## Background of the Invention

Inertially stabilized spaceborne off-gimbal pointing IRU and tracking systems have had a common system architecture. Referring to Figure 1, the off-gimbal IRU pointing system utilizes relative angle sensors, such as inductosyns, encoders, resolvers as feedback control sensors collectively simply referred to herein as resolvers, utilizes gimbals for pointing an optical boresight along a desired line-of-sight LOS, and utilizes an inertial reference unit IRU typically having integrated X, Y, and Z gyroscopes integrated as a base motion sensor referred to simply as the gyro. The IRU is coupled to a controller while the gimbals are coupled to gimbal motors controlled by the controller. Specifically, the off-gimbal IRU pointing system includes two single-degree-of-freedom gimbals stacked in an orthogonal orientation and mounted on a base that serves as a platform. The gimbals have respective gimbal motors for driving the gimbals to desired positions as sensed by the resolvers relative to a base. There is an elevation gimbal and motor and an azimuth gimbal and motor. The pointing direction of the off-gimbal pointing system is represented by a telescopic boresight axis  $X_p$ . The boresight axis and the line-of-sight LOS are colinear. The resolvers measure angular rotations of the gimbal positions relative to the mounting base. As such, there is an azimuth resolver for measuring a relative azimuth angle  $\phi$  of the azimuth gimbal and there is an elevation resolver for measuring a relative elevation angle  $\theta$  of

1 the elevation gimbal, as the gyro measures inertial angular  
2 rate motion.

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4 The base is a platform to which is coupled the gimbale  
5 mechanisms, including the gimbals, optics defining the  
6 boresight, the resolvers, and the gyro. The boresight is  
7 maintained along a line-of-sight to a target. The base  
8 coordinate frame is defined by the mounting orientation of the  
9 IRU. That is, the base and IRU coordinate axes are coincident  
10 and designated as  $X_b$ ,  $Y_b$ , and  $Z_b$ . The azimuth gimbal is defined  
11 to be mounted directly to the base. The gimbal azimuth axis  $Z_g$   
12 is nominally aligned with the vertical base axis  $Z_b$  of the IRU.  
13 Angular orientation about  $Z_b$  is designated as azimuth angle  $\phi$   
14 and is measured by the azimuth resolver mounted between the  
15 base and the azimuth gimbal. The elevation gimbal is mounted on  
16 top of the azimuth gimbal. The gimbal elevation axis  $Y_g$  is  
17 nominally oriented orthogonal to the azimuth gimbal. Angular  
18 rotations of the elevation angle  $\theta$  about the gimbal elevation  
19 axis  $Y_g$  is measured by the elevation resolver mounted between  
20 the azimuth gimbal and elevation gimbal. The boresight  $X_p$  for  
21 the pointing system is defined to be statically fixed in the  
22 elevation gimbal coordinate frame and orthogonal to the  
23 elevation gimbal axis  $Y_g$ . There is a coordinate frame  
24 associated with the azimuth gimbal ( $X_a$ ,  $Y_a$ ,  $Z_a$ ) and a  
25 coordinate frame associated with the elevation gimbal ( $X_e$ ,  $Y_e$ ,  
26  $Z_e$ ). Hence, there are three coordinate frames, the base frame  
27 ( $X_b$ ,  $Y_b$ ,  $Z_b$ ), the azimuth frame ( $X_a$ ,  $Y_a$ ,  $Z_a$ ), and the elevation  
28 frame ( $X_e$ ,  $Y_e$ ,  $Z_e$ ). A fourth reference frame is the boresight

1 pointing frame ( $X_p, Y_p, Z_p$ ). Because each of the gimbals only  
2 has a single degree of freedom, only rotational coordinate axes  
3 are used. The azimuth and elevation coordinate frames are  
4  $Z_a=Z_b$ ,  $Y_e=Y_a=Y_g$ ,  $X_p=Z_p$ ,  $Y_p=Y_e=Y_a=Y_g$ , and  $Z_p=Z_e$ . This leads to  
5 a transformation from base frame ( $X_b, Y_b, Z_b$ ) to the pointing  
6 frame ( $X_p, Y_p, Z_p$ ) by two Euler angle rotations  $\phi$  and  $\theta$  that are  
7 measured on the  $Z_g=Z_a=Z_b$  axis and the  $Y_g=Y_a$  axis. These two  
8 axis  $Z_g=Z_a=Z_b$  axis and the  $Y_g=Y_a$  axis are orthogonal.

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10 A zero readout position of the elevation resolver orients  
11 the boresight  $X_p$  to be orthogonal to the gimbal azimuth axis  
12  $Y_g$ . The zero readout position of the azimuth resolver orients  
13 the gimbal elevation axis  $Y_g$  to be coplanar with the base axis  
14  $Y_b$ . Because the gimbals only have a single degree-of-freedom  
15 rotational capability, the gimbal azimuth axis  $Z_g$  will be  
16 aligned with the base  $Z_b$  axis while the gimbal elevation axis  
17  $Y_g$  will always be parallel to the base plane defined by a  
18 horizontal base axis  $X_b$  and a vertical base axis  $Y_b$ . The base  
19 axis  $X_p$  has an angular rate  $\omega X_b$  indicating spatial rotation of  
20 the base. The boresight direction  $X_p$  can then be computed with  
21 respect to the base as a set of Euler angle rotations given by  
22 the resolver readouts. Because the IRU gyros measure the  
23 orientation of the base with respect to inertial space, the  
24 boresight can be transformed into an inertial coordinate frame.

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26 Referring to Figures 1 and 2, and more particularly to  
27 figure 2, an off-gimbal IRU control system controls the  
28 physical operation of the off-gimbal pointing system. The

1 controller C is a system controller for maintaining the  
2 boresight as a desired line-of-sight LOS. The control system is  
3 a dynamic system for maintaining a desired line of sight under  
4 closed-loop control. The controller provides direction signals  
5 to the gimbal motors that in turn provide torque to control the  
6 movement of the gimbals. The plant P represents a model of the  
7 inertia of the gimbals and provides a pointing angle for  
8 maintaining the boresight line of sight. The output of the  
9 plant P is the mechanical angular movement of the telescopic  
10 boresight about the  $Y_g$  and  $Z_g$  axes. External vibration and  
11 disturbances are effectively mechanically summed by the  
12 coupling of gimbals and telescope to the base through the  
13 compliance K that models a gimbal suspension system of the  
14 azimuth and elevation gimbals. The base motion M is received by  
15 the control system. The base motion M is sensed by the gyro, as  
16 the base motion M excites the modeled spring suspension defined  
17 by compliance K that is summed as a torque with to the gimbal  
18 drive torque. The resolver R provides the relative sensor  
19 feedback of the measured boresight angle relative to the base.  
20 The feedback for both resolvers is coupled to the controller.  
21 The gyro G is a feed forward inertial gyro sensor that provides  
22 the measured angular rates  $\omega_{Xb}$ ,  $\omega_{Yb}$ , and  $\omega_{Zb}$  of the base. The  
23 measured angular motion of the base motion M is coupled to the  
24 controller. An input command CMD is received by the controller  
25 and the controller provides the gimbal drive signals to torque  
26 the telescopic boresight to the commanded desired line-of-sight  
27 LOS. The purpose of the off-gimbal IRU pointing system is to  
28 control the telescopic boresight to be driven to and maintained

1 at the desired line-of-sight LOS in the presence of mechanical  
2 base motion and disturbances M. The gimbals, as modeled by the  
3 plant P, are inertially commanded to an orientation specified  
4 by the command CMD so as to point the boresight along the  
5 desired line-of-sight while attenuating the effects of  
6 mechanical disturbances of the base motion M.

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8 The off-gimbal IRU control system provides an analytic  
9 coupling of the base motion M with the gyro G and resolver R  
10 sensor measurements for dynamic closed-loop control of the  
11 telescopic boresight. The base motion M excites the gimbals as  
12 modeled by the plant dynamics P and through the gimbal  
13 compliance K. The suspension compliance K and resolver R both  
14 are affected by a sum of the line-of-sight movement and the  
15 base motion M. Essentially, the gimbal compliance K acts as a  
16 passive isolator in coupling base motion M to the inertia of  
17 the gimbals modeled by the plant P. The more compliant  
18 compliance K is, the more high frequency motion from the base  
19 is rejected. The deficient suppression of low frequency  
20 components of the base motion disturbance pass through the  
21 compliance K unattenuated for following the command CMD. The  
22 gyros G are used in a feed forward loop and resolvers R are  
23 sensors used in the closed-loop to drive the boresight to the  
24 desired line-of-sight LOS, but mechanical disturbances can  
25 produce unwanted motion of the gimbals as sensed by the  
26 resolvers. The gyro G and resolver R measurements to the  
27 controller C in the feedback control system of Figure 2, have  
28 frequency response components from the excitation of base

1 motion disturbance  $M$  that could be rejected. The system is  
2 designed to have a fast response time to maintain the boresight  
3 on the desired line-on-sight. The control system perfectly  
4 follows low frequency components of the base motion  $M$  to  
5 maintain the boresight on the desired line-on-sight.

6  
7       Ideal resolvers  $R$  measure the relative angle between the  
8 base and the gimbal orientation to infinite bandwidth. Ideal  
9 gyros  $G$  measure the inertial angle of the base with infinite  
10 bandwidth. Together, these two sensors measure the total  
11 motion of the boresight. By differencing or summing the  
12 resolver  $R$  measurements with the gyro  $G$  measurements, the  
13 direction of the line-of-sight  $LOS$  with respect to the input  
14 Command  $CMD$  is computed perfectly. The problem with this  
15 computation is that ideal resolvers and ideal gyros do not  
16 exist, but rather have a band-limited responses. As a  
17 consequence, there will be a residual error, which is a  
18 function of bandwidth when these two sensors are summed or  
19 differenced. When the bandwidth of the resolvers and gyros are  
20 well above the bandwidth of the control loop, for example by a  
21 factor of ten, then the bandwidth difference between the gyros  
22 and resolvers are negligible. The feedback control system will  
23 attenuate the effects of the sensor bandwidth mismatch whenever  
24 the mismatch occurs outside of the control loop bandwidth. If  
25 additional base motion rejection performance is desired, the  
26 design practice has been to increase loop bandwidth with the  
27 result that sensor bandwidths had to also increase. Increasing  
28 gyro bandwidths can be a costly. Typical bandwidths for

1 resolvers are about 1.0 kHz, while that of gyros for spaceborne  
2 applications are less than 50 Hz. Further, it is design  
3 practice to increase the bandwidth of gyros alone to achieve  
4 additional performance out of a control system. Conventional  
5 practices dictate that improving sensor response can only  
6 result in improved system response. This leads to efforts to  
7 increase the performance bandwidth of the lowest bandwidth  
8 sensor that is usually the gyros. To achieve this improved  
9 bandwidth response, there are significant cost increases of  
10 the gyro manufacturers. This is a disadvantageous limitation of  
11 the off-gimbal IRU design approach to base motion rejection.  
12 These and other disadvantages are solved or reduced using the  
13 invention.

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## Summary of the Invention

An object of the invention is to provide an off-gimbal pointing system with improved dynamic closed-loop control.

Another object of the invention is to provide an off-gimbal pointing system with improved dynamic closed-loop control by providing filtered measurement responses.

Yet another object of the invention is to provide an off-gimbal pointing system with improved dynamic closed-loop control by providing filtered resolver and gyro measurement responses.

Still another object of the invention is to provide an off-gimbal pointing system with improved dynamic closed-loop control by providing filtered resolver and gyro measurement responses using filtering.

A further object of the invention is to provide an off-gimbal pointing system with improved dynamic closed-loop control by providing filtering resolver measurement responses and filtering gyro measurement responses.

A conventional off-gimbal pointing system is improved with the addition of filtering of resolver and gyro measurement responses. Resolver filtering is applied at the output of the resolvers for attenuating at least high frequencies components

1 of resolver responses. Gyro filtering is applied at the output  
2 of the gyros for attenuating at least high frequency gyro  
3 responses. In the preferred form, the resolver filtering and  
4 gyro filtering shape the respective resolver and gyro responses  
5 to be matching in bandwidth that is greater than the closed-loop  
6 system bandwidth. By effectively degrading the high frequency  
7 measurement responses of the gyros and resolvers, the dynamic  
8 control of the off-gimbal pointing system is improved and  
9 suitable for reducing the effects of base motion disturbances.  
10 These and other advantages will become more apparent from the  
11 following detailed description of the preferred embodiment.  
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## Brief Description of the Drawings

Figure 1 depicts a conventional off-gimbal pointing system.

Figure 2 is block diagram of a conventional off-gimbal control system.

Figure 3 is block diagram of an improved off-gimbal control system.

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## Detailed Description of the Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the figures. Referring to all of the Figures, and more particularly to Figure 3, the improved off-gimbal control system includes the addition of a resolver shaping filter  $F_r$  and a gyro shaping filter  $F_i$ . The control system utilizes resolvers as feedback control sensors, utilizes gimbals for pointing an optical boresight along a desired line-of-sight LOS, and preferably utilizes an inertial reference unit IRU typically having integrated X, Y, and Z gyroscopes as base motion sensors. The IRU is coupled to a controller. The gimbals are coupled to gimbal motors controlled by the controller. The motors drive the gimbals to a desired position as sensed by the resolvers relative to the base. An elevation gimbal and motor and an azimuth gimbal and motor are used to position the telescopic boresight axis  $X_p$ , that is, the line-of-sight LOS. The azimuth resolver measures the relative angle of the azimuth gimbal. The elevation resolver measures a relative elevation angle  $\theta$  of the elevation gimbal. The resolvers measure angular rotations of the gimbal positions relative to the mounting base. The gyro measures inertial angular motion of the base.

The off-gimbal control system controls the physical operation of the off-gimbal pointing system. The controller C is a system controller for maintaining the boresight as a desired line-of-sight LOS. The control system is a dynamic

1 closed-loop system for maintaining the boresight at a desired  
2 line-of-sight. The controller C provides direction signals to  
3 the gimbal motors that controls the movement of the gimbals.  
4 The plant P is a model of the inertia of the gimbals and  
5 provides a pointing angle for maintaining the boresight line-  
6 of-sight LOS. The output of the plant is the mechanical  
7 movement of the telescopic boresight along the line-of-sight  
8 LOS. External vibrations and disturbances are effectively  
9 mechanically summed as a mechanical excitation coupled through  
10 gimbals and telescope to the base. The compliance K models the  
11 gimbal suspension system of the azimuth and elevation gimbals.  
12 The azimuth and elevation gimbals are a part of a gimbal  
13 system. The base motion M includes relative base motion such as  
14 the trajectory of a supporting spacecraft and vibration  
15 disturbances that are received by the base as angular rates of  
16  $\omega_{Xb}$ ,  $\omega_{Yb}$ , and  $\omega_{Zb}$  from the gyros. That is, the base motion is  
17 sensed by the gyros. The mechanical movements M and  
18 disturbances excite the modeled spring suspension. The  
19 compliance K is summed as a torque signal to the gimbal drive  
20 signals from the controller for maintaining the boresight along  
21 the desired line-of-sight LOS. The resolver R is a resolver  
22 system that provides the relative sensor feedback of the  
23 measured resolver angle for both the elevation and azimuth  
24 resolvers to the controller C. The gyro G is a gyro system that  
25 provides angular rates  $\omega_{Xb}$ ,  $\omega_{Yb}$ , and  $\omega_{Zb}$  to the gyro filter  $F_i$ .  
26 An input command CMD is received and is summed with filtered  
27 resolver responses from the resolver filter  $F_r$  and is summed  
28 with the filtered gyro responses from the gyro filter  $F_i$  by the

1 off-gimbaled controller as the controller provides the gimbal  
2 drive signals to drive the telescopic boresight to the  
3 commanded desired line-of-sight LOS during a closed-loop  
4 operation. The purpose of the off-gimbaled pointing system is  
5 to control the telescopic boresight to be driven to and  
6 maintained at the desired line-of-sight LOS in the presence of  
7 mechanical motion and disturbances  $M$ . The gimbals, as modeled  
8 by the plant  $P$ , are inertially commanded to an orientation by  
9 the specified command  $CMD$  so as to point the boresight along  
10 the desired line-of-sight while attenuating the effects of  
11 mechanical disturbances of the base motion  $M$ .

12  
13       The off-gimbal control system provides an analytic  
14 coupling of the base motion  $M$  with the gyro  $G$  and resolver  $R$   
15 sensor measurements for dynamic closed-loop control of the  
16 telescopic boresight. The base motion excites the gimbals,  
17 modeled by the plant dynamics  $P$  through the gimbal compliance  
18  $K$ . The suspension compliance  $K$  and resolver  $R$  are affected by a  
19 sum of the line of sight movement as provided by the plant  $P$   
20 modeling of the gyros and the base motion  $M$ . Essentially, the  
21 gimbal compliance  $K$  acts as a passive isolator in coupling base  
22 motion  $M$  to the inertia of the gimbals modeled by the plant  $P$ .  
23 The more compliant compliance  $K$  is, the more high frequency  
24 motion from the base is rejected. The deficient suppression of  
25 low frequency components of base motion disturbance pass  
26 through the compliance  $K$  unattenuated causing accurate pointing  
27 of the pointing system. The gyros  $G$  and resolvers  $R$  are sensors  
28 used during the closed-loop control to drive the boresight to

1 the desired line-of-sight LOS, but mechanical disturbances can  
2 produce unwanted motion of the gimbals and the base as  
3 respectively sensed by the resolvers and gyros. The filtered  
4 gyro and resolver responses are summed with the input command  
5 as a control input to the controller C as part of a feedback  
6 closed-loop control system having frequency response components  
7 from the excitation base motion disturbance M. The resolvers  
8 are in the closed-loop while the gyros are in a feed forward  
9 loop. The system is designed to have a fast response time using  
10 high frequency response gyros and resolvers to maintain high  
11 frequency performance with respect to maintaining the boresight  
12 along the desired line-of-sight commanded but with filtering of  
13 the gyro and resolver responses. By degrading high frequency  
14 components, and preferably matching the resolver and gyro  
15 effective filtered responses using the filters  $F_r$  and  $F_i$ , the  
16 control system maintains the telescopic boresight to be on the  
17 desired line-of-sight in the presence of base motion as well as  
18 motion of the telescopic boresight.

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20 The resolver R measures the relative angle between the  
21 base and the gimbal orientation. The gyro G measures the  
22 inertial angle of the base. Together, the resolver and gyro  
23 sensors measure the total motion of the boresight. By  
24 differencing or summing the resolver R measurements with the  
25 gyro G measurements, the direction of the line-of-sight LOS  
26 with respect to the input command CMD is computed. The  
27 resolvers and gyros have a high frequency band limited  
28 response. As a consequence, there will be a residual error,

1 which is a function of bandwidth, when these two sensors are  
2 summed or differenced. The bandwidth of the resolvers and gyros  
3 are well above the bandwidth of the control loop, for example  
4 by a factor of ten. The gyro and resolver need only a bandwidth  
5 equal to or greater than the system bandwidth of the control  
6 closed-loop. The resolver and gyro filtering effectively lower  
7 the operational bandwidth of the gyros and resolvers. As such,  
8 high frequency response component of the gyro and resolvers are  
9 attenuated so that residual errors in the high frequency domain  
10 from the gyro and resolver are reduced. Hence, the feedback  
11 control system will attenuate the resolver and gyro responses  
12 in the high frequency domain, for improved performance. As  
13 such, lower frequency and consequently less costly resolvers  
14 and gyros may be used. The bandwidths for resolvers are about  
15 1.0 kHz, while the bandwidth of the gyros for spaceborne  
16 applications are about 60 Hz, and while the responses of the  
17 closed-loop system is about 10 Hz. The filtering may have a 0.2  
18 kHz pole for reducing high frequency components above 0.2 kHz.  
19 Preferably, the filtered frequency responses of the resolvers  
20 and gyros are match and have an upper pole at 50 Hz, such that  
21 both filtered responses are degraded and matched but remain  
22 greater than the 10 Hz closed-loop control system bandwidth  
23 response. As such, the control closed-loop system is not  
24 excited at the input of the controller with unwanted high  
25 frequency signals outside the frequency response of the control  
26 system. Those skilled in the art can make enhancements,  
27 improvements, and modifications to the invention, and these  
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1 enhancements, improvements, and modifications may nonetheless  
2 fall within the spirit and scope of the following claims.

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